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STEREOPHOTOGRAMMETRIC INVESTIGATION OF AIR FLOW IN THE
BOUNDARY LAYER OF THE ATMOSPHERE ABOVE A HILL

[Stereofotogrammetricheskoye issledovaniye vozdušnogo potoka v
pogranichnom sloye atmosfery nad kholmom]

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PRICES SUBJECT TO CHANGE

STEREOPHOTOGRAMMETRIC INVESTIGATION OF AIR FLOW IN THE BOUNDARY LAYER OF THE ATMOSPHERE ABOVE A HILL

V. S. Yelisseyev

INTRODUCTION

In recent years, ground stereophotogrammetric methods of investigation have been used extensively in the national economy. The extensive use of ground stereophotogrammetric recording is explained by many of the advantages it alone possesses with respect to many other methods. One of its principal advantages is the fact that photographic images may be used for highly accurate measurements of the coordinates of an object in three-dimensional space. The photographic method also makes it possible to determine the effect of short-term processes and to break down complex ones into individual phases.

Stereophotogrammetric methods are also used for geophysical research. There have been studies involving investigation of disturbances by means of stereophotogrammetric recording [8] as well as a number of problems involving the study of the physics of the upper atmosphere, where they are one of the principal means of studying air currents and diffusion characteristics at heights of 50-200 km [17].

This method can be used successfully for investigating the structure of the wind and turbulent characteristics in the boundary layer of the atmosphere.

The pibal method is currently used to obtain wind profiles in the lower layers of the atmosphere. However, this method provides a determination of only integral wind speed in the successive layers of the atmosphere. Obtaining further details from a wind profile obtained in this fashion is limited both

as regards the technique of tracking the movement of the pibals and the insufficient reaction of the latter to various kinds of air movements, especially as the scale of the wind movements decreases [19].

Another approach to the solution of the problem under discussion is the use of a number of remote controlled anemometers fastened to the cable of a captive balloon. In this case, it is necessary to take into account not only certain difficulties involved in maintenance, but also the practical absence of the possibility of installing several captive balloons if it is necessary to obtain the spatial structure of the air current.

Recently, meteorologists have begun to use tall masts with wind sensors mounted upon them. An example of such a mast in the USSR is the 300-meter meteorological tower in Obninsk. Tall masts, which are currently one of the best ways of determining the vertical profile of the wind in the lowest 300-500 meters of the atmosphere, have a number of shortcomings. The main disadvantages of their wide use are the following: lack of mobility, high construction and maintenance costs, and the dangers posed to aviation.

In this connection, attempts have been made in a number of countries to develop a method of obtaining the wind profile which would be free of the above shortcomings. These methods include photographing the drift and deformation of an initially produced vertical plume of smoke, formed by a falling smoke rocket, or a column of smoke, produced by a special smoke cartridge launched from an aircraft.

One version of this method was used in 1952 by the Cambridge Aviation Research Center in collaboration with the Geophysical Research Directorate [16]. An aviation smoke charge was thrown from a helicopter at approximately 1.5 km, releasing a smoke trail behind it which was photographed. However, the production of a continuous smoke trail encountered a number of technical difficulties. Hence, in subsequent experiments smoke cartridges were fastened to a steel cable and the cable was elevated by means of the helicopter. When an electrical pulse was transmitted, the explosion of the detonators of the cartridges produced a smoke cloud rather than a stream.

The first elevation of the 200-meter cable by helicopters took place in February, 1953. The method turned out to be extremely difficult, because when suspended freely the lower end of the cable was deflected 600 meters in the direction of the wind and frequently was damaged by coming in contact with the ground. Recovering the very long and cumbersome cable after each experiment required too much time and thereby prevented continuous operation according to the program. The tests also showed that the visibility and permanence of the smoke cloud was very good. Determination of the spatial coordinates of the smoke cloud was accomplished graphically by means of special calibrated nomograms.

Recently a group of experiments was performed in the GDR involving photography of smoke trails from smoke cartridges ejected from aircraft and smoke trails produced by special falling cartridges launched by mortars. Photography was accomplished with two aerial cameras using the "normal case" of photography, and the negatives were analyzed on a highly accurate stereocomparator [14].

The last decade has been characterized by increasing attention being paid by investigators to the problems of atmospheric pollution. The solutions which have been found in conjunction with the dispersion of pollutants from large industrial sources pertain to areas with relatively flat surfaces [2, 18 and others]. However, many of the sources have been located in areas with rather complex relief, where the spatial distribution of the wind has its own characteristics.

There are a number of theoretical [7, 10, 11] and microclimatic experimental [9, 12] works involving a study of the influence of complex forms of relief on air flow. These data in microclimatic research refer to the layer of air near the ground up to altitudes of two to four meters, while the theoretical work is associated with a certain stylization of the statement of the problem. In this connection, the Main Geophysical Observatory imeni A. I. Voyeykov has performed a number of experiments both theoretical [3, 4] and experimental [6] involving the study of the influence of complex small-scale relief forms on

the structure of the flow and the dispersion of the pollutant. One such work is the development of methods of ground stereophotogrammetric recording to determine the coefficients of turbulent fusion on the basis of the visual appearance of smoke streams and the detection of regular features of the structure of the wind field above inhomogeneous and complexly-shaped reliefs.

DEVELOPMENT OF THE METHOD

The use of methods of ground stereophotogrammetric recording to investigate the structure and diffusion characteristics of air flow in the boundary layer of the atmosphere is possible with four basic components, by means of which a total solution can be found to the problem. These are: trace methods of producing smoke trails, stereophotogrammetric apparatus, automatic apparatus for processing the pairs of stereo pictures, an electronic computer for solving the algorithm of transformation of the coordinates of the object in question and calculation of the necessary parameters of the air flow structure.

Inasmuch as we adopted the analytical method (as the most precise) for photography jointly with the Moscow Institute of Geodetic Aerial-Photographic and Cartographic Engineers as the basis of solving the equations of the relationship between the coordinates of the investigated targets and the coordinates of their images, a universal device was built for ground stereophotogrammetric recording of smoke trails and made it possible to utilize the "general case" of photography [5]. The recording device was built on the basis of the AFA-41/20 Soviet-made aerial cameras, combined with highly accurate optical theodolites. The use of aerial cameras instead of the usually employed photo theodolites is explained by the fact that the small size of the photographic plates used in the phototheodolite produces an increase in the error factor of the method, since the decrease in the scale of the photograph increases errors in measuring spatial coordinates. In addition, the minimum discreteness of the photographs taken by a camera is 2.2 seconds instead of 1-2 minutes. Photography was carried out using black and white or color film in a 19 x 19 cm format. To exclude the influence of deformation of the film used for aerial photography,

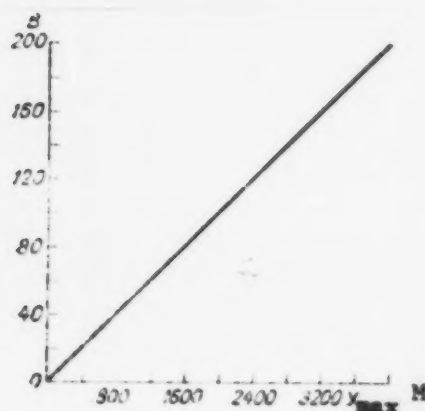


Figure 1.

it was clamped against a piece of glass with coordinate crosses marked on it over the entire image area, so that they would appear in the photograph. Figure 1 shows the possible spatial scale of a photograph made with this apparatus for $Y_{\max}$: this same scale is used for the following characteristics:

$Y_{\max}(M)$	400	800	1200	1600	2000	2400	2800	3200	3600	4000
$Y_{\min}(M)$	80	160	240	320	400	480	560	640	720	800
Depth of Photography	320	640	960	1280	1600	1920	2240	2560	2880	3200
Horizontal Coverage (M)										
Max	360	720	1080	1440	1800	2160	2520	2880	3240	3600
Min	72	144	216	288	360	432	504	576	648	720
Area Photographed (km ²)	0.069	0.276	0.622	1.106	1.728	2.488	3.387	4.424	5.599	6.912
$h_{\max}(M)$	180	360	540	720	900	1080	1260	1440	1620	1800
$h_{\min}(M)$	36	72	108	144	180	216	252	288	324	360

To ensure the effectiveness of the analytical method of analyzing the stereo pairs, the normal stereo comparator was replaced by an automated precision stereocomparator known as the "Stekometr" and a computer. As a result, the

resolution of the coordinates alone was increased five to seven times in comparison with a normal stereocomparator, and the operator error was eliminated as well. The average measurement accuracy of the coordinates is $\pm 2 \cdot 10^{-3}$ mm. By means of an automatic strip-chart recorder, it was possible to automatically record the results of the measurements on a decade counting system using paper blanks, and punching the data obtained onto a punched tape makes it possible to perform calculations using specially written programs directly on the M-220 computer. Hence, using the automatic instruments to record the coordinates and the computer makes it possible to carry out precise calculations of a very large number of points.

As the basis for producing the smoke trails, standard pyrotechnic devices were employed that allowed the production of vertical orange trails starting at the ground. These devices are safe to use and comparatively inexpensive. The smoke trail which is produced lasts for about one minute, and the color characteristic provides additional color contrast in addition to brightness contrast, thus making it possible to obtain a good image on the photographic negatives with any kind of photographic background.

DETERMINING WIND SPEED ON THE BASIS OF STEREOFOTOGRAPHS AND ANALYZING ERRORS

Let us deal with some of the problems that are associated with the accuracy of computing wind speed on the basis of stereophotographs of vertical smoke trails.

Let X_{01}, Y_{01}, Z_{01} be the spatial coordinates of the axial points of a smoke trail, produced at the initial moment in time t_0 . The values of these coordinates for the "normal case" of photography are determined by the formulas:

$$X_{01} = Bx_{01}p_{01}^{-1}; \quad (1)$$

$$Y_{01} = Bf_k p_{01}^{-1}; \quad (2)$$

$$Z_{01} = Bz_{01}p_{01}^{-1}. \quad (3)$$

Due to the shifting of the basic points in the wind field, spatial coordinates of these same points will acquire new values. X_{11}, Y_{11}, Z_{11} . Then formulas (1) - (3) to determine the numerical values of the coordinates will be written as follows:

$$X_{11} = E x_{11} F_{11}^{-1}; \quad (4)$$

$$Y_{11} = B f_k p_{11}^{-1}; \quad (5)$$

$$Z_{11} = F z_{11} p_{11}^{-1}. \quad (6)$$

Consequently, spatial coordinates of the path traveled by the basic points due to their transport by the wind, if we disregard the small term $(p_{01} \Delta p)$, will be

$$\Delta X = B_1 [(x_{11} - x_{01}) p_{01} - x_{01} \Delta p] p_{01}^{-2}; \quad (7)$$

$$\Delta Y = B f_k p_{01}^{-2} \Delta p; \quad (8)$$

$$\Delta Z = B [(z_{11} - z_{01}) p_{01} - z_{01} \Delta p] p_{01}^{-2}. \quad (9)$$

Hence, on the basis of observations of two stereo pairs, obtained at two moments in time with a specific time interval, the speed and direction of the wind and its components along axes X, Y, Z are determined. Hence, from (7) - (9), we have

$$\Delta X = \Phi_1(B, x_{11}, x_{01}, p_{01}, \Delta p),$$

$$\Delta Y = \Phi_2(B, f_k, p_{01}, \Delta p),$$

$$\Delta Z = \Phi_3(B, z_{11}, z_{01}, p_{01}, \Delta p),$$

$$\Delta p = \Phi_4(p_{11}, p_{01}).$$

The squares of the average errors in the displacement of the individual points in the smoke trail along axes X, Y, and Z are written as follows:

$$S_{\Delta X}^2 = \left(\frac{d \Delta X}{d x_{11}} \right)^2 S_{x_{11}}^2 + \left(\frac{d \Delta X}{d x_{01}} \right)^2 S_{x_{01}}^2 + \left(\frac{d \Delta X}{d p_{01}} \right)^2 S_{p_{01}}^2 + \left(\frac{d \Delta X}{d p_{11}} \right)^2 S_{p_{11}}^2; \quad (10)$$

$$S_{\Delta Y}^2 = \left(\frac{d \Delta Y}{d B} \right)^2 S_B^2 + \left(\frac{d \Delta Y}{d f_k} \right)^2 S_{f_k}^2 + \left(\frac{d \Delta Y}{d p_{01}} \right)^2 S_{p_{01}}^2 + \left(\frac{d \Delta Y}{d p_{11}} \right)^2 S_{p_{11}}^2; \quad (11)$$

$$S_{\Delta Z}^2 = \left(\frac{d\Delta Z}{dB}\right)^2 S_B^2 + \left(\frac{d\Delta Z}{dz_0}\right)^2 S_{z_0}^2 + \left(\frac{d\Delta Z}{dz_1}\right)^2 S_{z_1}^2 + \left(\frac{d\Delta Z}{d\rho_{01}}\right)^2 S_{\rho_{01}}^2 + \left(\frac{d\Delta Z}{d\rho_{11}}\right)^2 S_{\rho_{11}}^2 \quad (12)$$

Having determined the values of the derivatives for equations (10) - (12) and disregarding the small terms, we find that the theoretical value of the mean square error in wind speed for time interval Δt , with $S_{\rho_{01}} = S_{\rho_{11}} = S_p$; $S_{x_{01}} = S_{x_{11}} = S_x$ and $S_{z_{01}} = S_{z_{11}} = S_z$ will be:

$$S_v = A^{1/2} \Delta t^{-1/2}, \quad (13)$$

where

$$A = 2B^2 p^{-1} (S_p^2 p^2 + S_x^2 x_1^2 + S_z^2 z_1^2 + S_p^2 p^2) + 2\Delta Y^2 S_p^2 \Delta p^{-2}.$$

In calculating the mean wind speed using several realizations N , we have

$$S_{\bar{v}} = A^{1/2} N^{-1/2} \Delta t^{-1/2}. \quad (14)$$

Finally, the mean square error of the pulsations in the wind speed is

$$S_{v'} = A^{1/2} \Delta t^{-1/2} (1 + N^{-1})^{1/2}. \quad (15)$$

By giving numerical values for the original parameters, which are close to the values obtained in the experiment described, we see that, if $B = 135 \text{ m}$, $\Delta t = 3 \text{ sec.}$, $\Delta Y = 3 \text{ m}$, $N = 5$, $x_1 = 60 \text{ mm}$ and $z_1 = 40 \text{ mm}$:

$$S_v = 0.24 \text{ m/sec.},$$

$$S_{\bar{v}} = 0.11 \text{ m/sec.},$$

$$S_{v'} = 0.29 \text{ m/sec.}$$

It should be mentioned in this connection that the error may change over the field of the photograph as a function of x_1 and z_1 .

Using the smoke trail photographs for calculation, we obtain a wind speed for rather short time intervals. However, it is frequently necessary to obtain the average wind profile for a time on the order of 10 minutes. In this case it is necessary to determine how necessary it is to make stereo pairs of smoke trails to obtain reliable 10-minute average values for wind speed.

Assuming that the distribution of velocity components above a flat surface obeys the Gaussian Law (such a distribution of speeds is indicated in [16]), the probability density of the velocity pulsations is written as follows

$$F(u') = \frac{1}{\sqrt{2\pi} \sigma} \exp\left[-\frac{u'^2}{2\sigma^2}\right], \quad (16)$$

where the pulsation speeds are calculated relative to the selected averages.

Then the probability that the average values for the speed from N runs will differ from the 10-minute average is no greater than the value of α is determined from the Laplace function:

$$2H(z) = \frac{2}{\sqrt{2\pi}} \int_0^z \exp\left[-\frac{t^2}{2}\right] dt, \quad (17)$$

where

$$z = \frac{u' \sqrt{N}}{\sigma},$$

However, Durst [13] has shown that with correlation equal to 0.87 for the wind speed, varying from 4 to 18 m/sec.,

$$\sigma(10 \text{ min.}, 5 \text{ sec.}) = -0.2 + 0.14 V.$$

With this relationship of the value σ to the 10 minute average air flow speed, formula (17) for the problem discussed above concerning the necessary number of discrete measurements will be

$$2H(z) = \frac{2}{\sqrt{2\pi}} \int_0^{\frac{u' \sqrt{N}}{-0.2 + 0.14V}} \exp\left[-\frac{t^2}{2}\right] dt. \quad (18)$$

Given that $2 \theta(c) = 95\%$ and $\alpha = 0.5$ m/sec., we find that with $V = 4$ m/sec. $N = 2$ and with $V = 10$ m/sec. $N = 23$.

The calculations above pertain to the case when the distribution of the velocity components obeys the Gaussian Law. When there is a complex relief, the distribution of the velocities may not obey this law, and the question of the time averaging cannot be solved in this fashion. At the same time, however, if we consider a hill as a characteristic minimum distance at which the dynamic effect of the hill itself can be felt, $\bar{T} = \frac{\bar{L}}{V}$, where $\bar{L}$ is the characteristic scale of the obstacle, i.e., the length of the hill, while $\bar{T}$ is the characteristic time. Then, with a change in wind speed from 2 to 20 m/sec., with $\bar{L} = 500$ m the characteristic averaging time will change from 4 minutes to 25 seconds. At an average wind speed of 5 m/sec $\bar{T} \approx 2$ min.

EXPERIMENTAL STUDIES OF AIR FLOW AROUND A HILL

Obtaining all four components of the use of the stereophotogrammetric method of ground photography of smoke trails made it possible in the summer of 1969 to carry out an experiment in the Razdan river valley to study the spatial structure of the air flow over a hill under natural conditions. The experiment was performed with the participation of associates from the MGO (Ye. L. Genikho-vich, A. S. Zaytsev, N. M. Ivanova and others), from the Moscow Institute of Engineers of Geodesy, Aerial Surveying and Cartography (B. A. Novakovskiy, V. V. Sintsov) and the Office for Rationalization and Inventions of the Administration of the Hydrometeorological Service of the Armenian SSR (G. E. Kosoyan).

In accordance with the problem to be studied, a hill approximately 100 meters high and 500 meters long was selected in the valley. The sides of the hill, covered with grass scorched by the sun, had a 15-30° slope.

Vertical smoke trails, orange in color, were produced above the hill (Figure 2); these trails were then photographed by the stereophotogrammetric apparatus with a 135 meter base between the cameras. Photography was carried out using black and white and color reversal film (type Ts0-2) with continuous

photography at intervals of three seconds until the smoke trails had completely dissipated. Gradient observations were conducted near the locations of the stereophotogrammetric apparatus to determine the air temperature and the wind speed.



Figure 2.

A total of approximately 500 stereo pairs was made, with photography being conducted both in the morning and evening hours. Further analysis of the data was conducted on the "Stekometer".

To determine the wind speed on the basis of the principal axes of the smoke trails, photography at minimum time intervals is of very great importance. The shorter the interval between the successive stereo pictures, the easier and more accurate it is to measure the spatial coordinates of the shifting of the trails, since the appearance of the elements of the smoke trails due to diffusion changes insignificantly in a three-second interval. Hence, it is possible to determine almost without error the identification of these elements

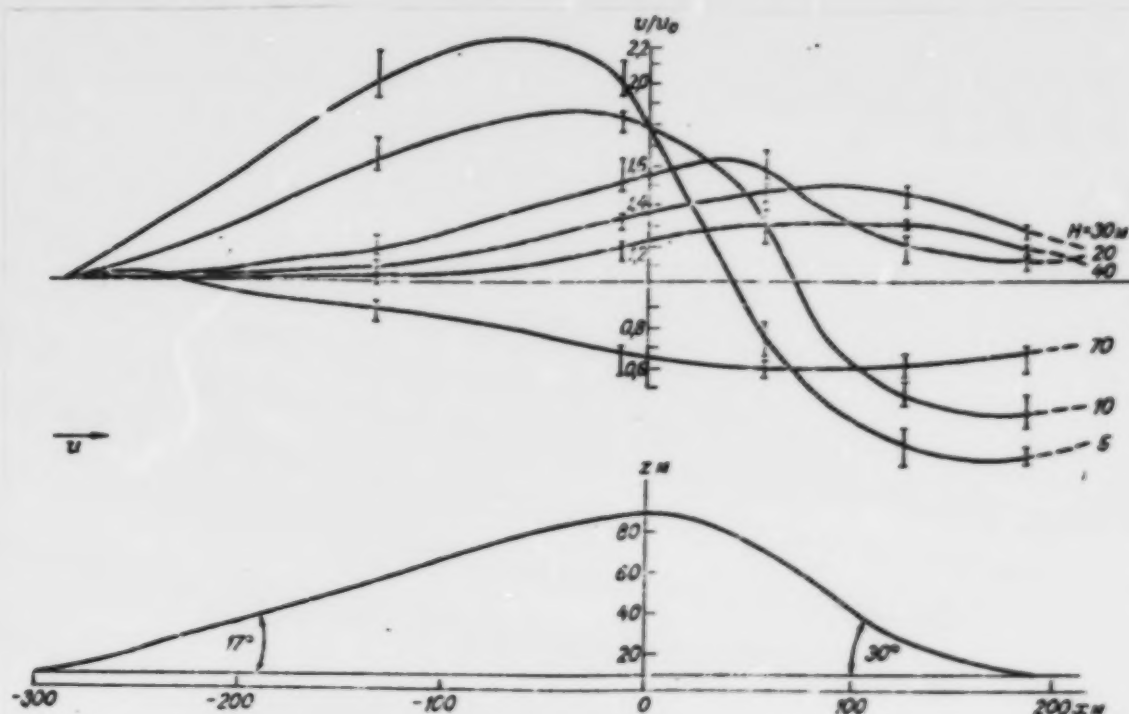


Figure 3.

on two successive stereo pairs. The analysis of the material was carried out both on the basis of the axial points at the boundaries of the trail and at a constant height interval. Comparison of the two methods of determining the wind profile showed good agreement. Transformation of the stereophotogrammetric coordinates into spatial ones and determination of the wind speed vector and its components were conducted on the M-220 computer in accordance with a specially written program.

A complex spatial picture of the actual flow of air over a ridge located perpendicular to the general flow can be used to determine the profiles of three velocity components and the total wind speed and direction. Due to the lack of temperature sounding, the differences in the wind profile were viewed solely from the viewpoint of the dynamic influence of the hill on the flow.



Figure 4.

The influence of the ridge of the hill, which was about one kilometer distant from the experimental site, is excluded by selecting a thickness of the investigated boundary layer sufficiently small in comparison with the distance to the ridge ($\frac{H}{x} = 0.1$).

The existence in Figure 2 of the visual images of local deflections indicates the presence in the velocity field, together with the large disturbances, of smaller variations as well. Such small scale disturbances are clearly linked to the development of disturbances in the zone of velocity and temperature gradients.

In Figure 3, as an example, we have shown the distribution of the relative velocities u/u_0 for various cross sections of the hill. Here u_0 is the air flow rate at a distance of 50 meters from the base of the hill. In as much as the photographs were made at an interval $\Delta t = 3$ sec., the vertical lines in the Figure show the extreme deviations of the absolute values u/u_0 for a two-minute time interval. Due to the low contrast of the pictures of the lower part of the smoke trail, the minimum altitude at which it is possible to detect displacement of the trail is five meters.

It is clear from Figure 3 that at the leading edge of the hill there is a gradual increase in wind speed up to heights of 40-50 meters. Maximum relative velocity at heights of 5 to 40 meters decreases from 120 to 30% with respect to the speed in the incident flow with its displacement from $x = 250$ m ($H = 5$ m) to $x = 470$ m ($H = 40$ m). Behind the hill the flow is braked to 70% at a height of 5 meters. The isolines u/u_0 generally resemble the configuration of the hill, but as we have already mentioned above, there is a displacement

of the maximum opposite the flow at $H = 5$ m and with flow from the top of the hill at greater heights.

At a height of 70 meters, a configuration of the isolines has a mirror image which means that the windward and lee sides of the hill are characterized by a decrease in wind speed in comparison to the incident flow and lower values for $u/u_0 = 30\%$ ($x = 350$ m) are located on the windward side of the hill.

Figure 4 shows the vertical distribution of the relative velocities u/u_0 at various sections of the hill: at a distance $x = -150$ m from the summit of the hill (1); below the summit of the hill (2); on the windward side of the hill at a distance of $x = 100$ m (3). It is clear from the graphs in Figure 4 that the 50-meter layer of air behind the hill is characterized by increased wind speeds, while the 15-meter layer as measured from the surface of the ground has reduced wind speed. The direction of the air flows in this layer is counter to the total flow toward the hill. An elliptical vortex is formed with semiaxes $a_1 = 75$ m and $a_2 = 100$ m with wind speeds in the lower part of 0.5 m/sec and 2.5 m/sec in the upper part. The maximum variation in the relative wind speed is observed at an altitude of 5 m above the surface of the hill with a gradual decrease in the absolute value u/u_0 with increasing altitudes. The increase in wind speed in the front part of the hill is noted in [1] as well, where, according to observational data on the flight of balanced damping balloons at slopes $\alpha = 10^\circ$, it was found that the maximum wind speeds are observed at an altitude of 4-6 meters above the surface of the slope and amount to 6-8 m/sec. According to our data, the wind speed in the middle portion of the hill at an altitude of 5 meters was 5.5 m/sec. But if the vertical profile u/u_0 in the middle part of the windward slope has a maximum at an altitude of 5 meters, drops sharply to an altitude of 20 meters and then slowly decreases to the 50 meter level, the profile at the top of the hill shows a continuous gradual decrease to an altitude of 50 meters.

Further analysis of the material will make it possible to study all three component wind velocities at various levels on the hill, and also will reveal features of the structure of the air flow during the morning and evening hours.

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